Geometric Shape, Structure and Material in Antoni Gaudí's Work: The Colònia Güell Crypt and the Templo Expiatorio de la Sagrada Familia

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Abstract: This paper is aimed at promoting a reflection on architect Antoni Gaudí's experimental method in the search for understanding the definition of the forms, structures, and constructive techniques applied by him in his various works, as in his processes of experimentation and formal modeling. In his legacy in the field of civil construction, we can highlight the development of the funicular method, known by the structural analysis and definition methodology that allows, in an original way, for the creation of the base geometry of his constructive elements through the association of traction experiments to their deformations and loads along their structure. In the field of architecture and civil engineering, the study of constructive techniques based on basic concepts of descriptive geometry and experimentation is of great importance in the field of digital technologies, as it enables the advancement of structural efficiency and plasticity, reinforced by the form-finding parametric modeling method currently. Therefore, to establish a parallel between the formal analysis worked by the Catalan architect and the current approaches of digital modeling, two of his works, Templo Expiatorio de la Sagrada Familia and Iglesia de la Colònia Guell, will be highlighted, which will be studied for their technical and formal effectiveness with the aid of parametric modeling programs.

Key words: Experimentation, structural efficiency, structural plasticity, form finding, parametric modeling.

1. Introduction

The study of the structures of nature is relevant in civil construction until the present time, because these forms are associated with the effort acting efficiently. Therefore, three real cases stand out: the hyperboloid of revolution in the bone matrix; the hyperbolic paraboloid in the leaves and roots of the trees; and the elliptical paraboloids in the shells. Man was influenced by the local and environmental context by developing different shelters, for example, in the Arctic the Igloo is built in double compressed curvature, in contrast to the thin traction double curvature tents produced in the desert from animal hide [1].

Silva and Souto [2] highlight three factors that define the relationship between architectural design and structure: the first factor is the functional one, in order to structure the space for different uses, such as housing, schools, airports; the second factor is technical characteristics related to the construction processes employed, such as mechanical strength of materials, balance and stability; the third factor is aesthetics in the composition of buildings; this aspect conveys to viewers, through geometric shapes, the proportion of space, sensations of balance and stability.

In the context of the most efficient structures, we tried to retrieve the concepts of the past by masters of architecture and engineering who adopted experimental methods to produce a multiplicity of forms. Meirelles and Kishi [3] highlight that Antoni

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Gaudí, Eduardo Torroja, Pier Luigi Nervi, Felix Candela and Frei Otto contribute to the study of the efficiency of form, for their precise methods. Each one applied different constructive, techniques permeated with a symbolic and tectonic character, in search of forms that associate the most efficient response to local materials.

Antoni Gaudí (1852-1926) is considered one of the greatest exponents in the search for structural efficiency, by testing funicular curves for purely traction structures and their adaptation to local materials that have a higher compressive strength, such as stones and masonry. Throughout this design process the Catalan architect made use of different methods of experimentation covering fields such as: analytical geometry, study of natural structures, analysis of materiality and curved shapes; this process has made it possible to further explore complex geometric shapes [4].

In an effort to reduce the constructive difficulties of curved shapes at the time, some architects experimented with geometries recognized for complying with the Membrane Theory by defining minimal surface tensions. Oxman [5] highlights the contribution of Antoni Gaudí and Frei Otto as the architects who gained in their journey a greater understanding of formal experimentation methods, the first through his Funicular Method and the latter for the Surface Tension Method, granting them the importance, although indirect, of deepening the physical-digital parameters for structural analysis, currently known as form-finding [6].

Digital modeling of complex curved surfaces began to be applied between 1970 and 1980; however it was effectively implemented in construction in the late 1990s. In parametric modeling the objects are mathematical components such as urban ventilation, thermal comfort, and the structure of complex forms, controlling their attributes of geometry, loading and mechanical properties, among others [7, 8].

This research aims to promote a reflection on Antoni Gaudí's experimental method in order to understand the definition of forms, constructive techniques and structure, applied in the context of two of his works: Iglesia de la Colònia Güell (Santa Coloma de Cervelló, Spain) and Templo Expiatorio de la Sagrada Familia (Barcelona, Spain) through parametric modeling.

2. Method

The research makes use of instruments of deconstruction and modeling of the geometric elements applied by Antoni Gaudí to understand the rebounds between morphology, structure and constructive technique. Oxman [5] considers that the morphological principles associate the geometric form as response to the loads and deformations. To this end, two of his works will be evaluated as a case study:

• Iglesia de la Colònia Güell (Santa Coloma de Cervelló, Spain);

• Templo Expiatorio de la Sagrada Familia (Barcelona, Spain).

As for its elaboration, the research is directed in five stages:

(1) Bibliographic review of authors who analyzed Antoni Gaudí's works and approached the form, the structural conception and his constructive techniques, as well as texts that evaluate Gaudí's rereading by his parametric modeling. This stage has a qualitative character through secondary sources.

(2) In this stage we analyzed the main applied geometric shapes of Antoni Gaudí, highlighted in both case studies through digital models.

(3) Field study with visits to the works located in Santa Coloma de Cervelló (Spain) and Barcelona (Spain), where images of Antoni Gaudí's works were collected to conduct this study as well as contact with primary sources.

(4) The parametric modeling performed only in the case study of the Sagrada Familia church (Barcelona, Spain) in order to gain a better understanding of the general structural behavior in relation to its loading, stresses. In the parametric modeling, we used the

Rhinoceros 6 software and the visual programming language tool Grasshopper version 6.1.18023.13161.

The elaborated analysis started from the main structure of the work, with the aid of floor plans and sections, seeking to establish a parallel between Antoni Gaudí's funicular arches and the form and finding concepts of digital modeling.

(5) Critical analysis of Gaudí's experimental process in these two works on the forms, structure and materiality, and the constructive process as well as the rebounds between the physical experiment and the digital modeling.

3. Results and Discussions

Antoni Gaudí is recognized in areas such as civil engineering, architecture, plastic arts and design for innovating through experimentation methods, exploring the form, plasticity and constructive possibilities of local materials. Two works will be analyzed: Colònia Güell Crypt of the Expiatorio de la Sagrada Familia temple and the Sagrada Familia church, due to different authors pointing parallels between the two works and due to the fact that a clear evolution between these two works is declared. Some of the main strategies were applied by Gaudí in the definition of forms: through funicular elements, curved surfaces that fit the membrane theory.

3.1 Gaudi's Method—Funicular Curves

Giralt-Miracle [4] notes that Gaudí sought to combine the most efficient structural solutions to obtain the desired spatiality in the architectural concept. Based on experiments and observations, the architect broke with the values of traditionalist architecture, using the funicular method. In this system he sought to determine the path of stress in the structure without the application of mathematical formulas. The method consists in the construction of a model with wires or ropes attached at its ends forming different curves depending on the load, including catenary (due to its own weight), the parabolic shape (loads distributed in identical horizontal intervals) and the third is formed by concentrated loads, representing the highest points of the churches. In the model, weights were proportional to the full-scale loads of the work (Fig. 1). The author notes that the wire is susceptible to loading, so the geometric shape represented the path of stress. At the end of the experiment a mirror was placed at the base of the model highlighting the compressed shape, and measurements were made on the traction model, and the design was inverted [9, 10].

Fig. 1   **(Left) weights and wires model; (right) model of the final work of the Sagrada Familia.**
Source: the authors.

Gaudí's method was directly related to local materials, such as stone and masonry called rasilla. The use of these materials in his works gave Gaudí the improvement in the study of compressed geometric forms and in the creation of his own conception of differentiated spaces with the composition of the forms [11].

3.2 Main Surface Elements Applied by Gaudí and Their Decomposition

Double curvature surfaces that comply with the membrane theory are considered more efficient when compared to simple ones [12]. In addition to this characteristic, Gaudí sought double curvature surfaces that could be generated by straight lines, known as ruled surfaces, in order to make their construction feasible.

Figs. 2-4 present the general forms used by Gaudí and their deconstructions.

Gaudí's ruled curved shape experiments have surpassed his era; many researchers consider that these experiments have an influence on parametric modeling on the concept of form-finding, as noted by Burry and

Burry [13]. Fig. 2 shows the discretization of a parallelogram and its modification by form-finding in hyperbolic paraboloid, as well as elements transformed into helical stairs.

The surface of a revolution hyperboloid is generated when its generating curve is hyperboloid, it can be defined by straight and sloping lines between the circles. It can be generated by one sheet, as shown in Fig. 3 (as the four figures show) or two sheets forming two domes as shown in the last image of Fig 3. Gaudí applied this form to different elements, from pillars, openings in the ceilings and closures of the Sagrada Familia to capture the light.

The hyperbolic paraboloid allows different geometric compositions, as shown in Fig. 4. The shape can be discretized or parameterized by straight lines, facilitating its construction. In both works analyzed this form can be observed in the vaults of the La Colonia Guell Crypt (Fig. 14) and in the towers of the Sagrada Familia. The tower's final shape starts from twelve hyperbolic paraboloids.

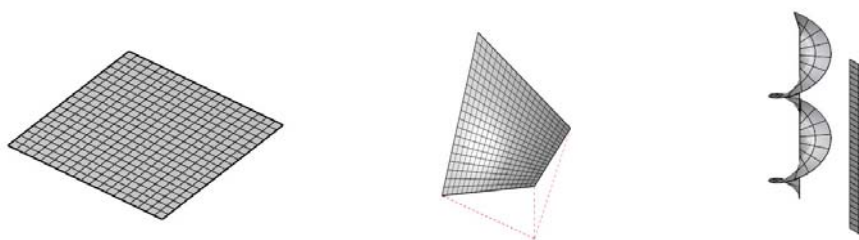"The hyperbolic paraboloid is one of the most

Fig. 2 (Left) a parallelogram base forms; (middle) hyperbolic paraboloid; (right) helical.
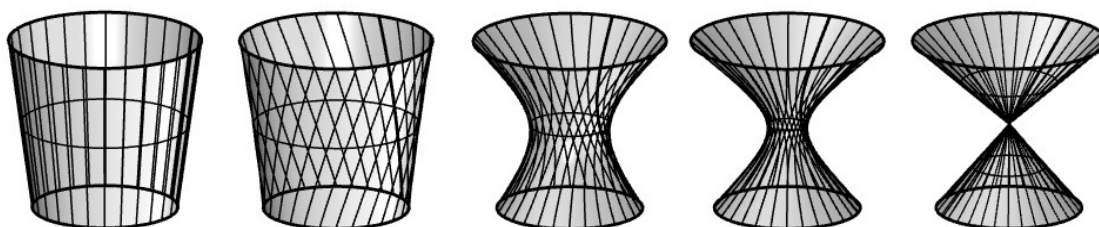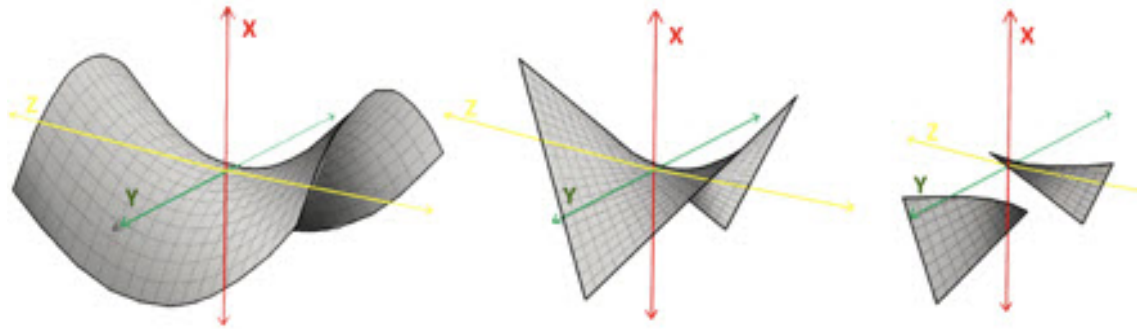Source: the authors.

Fig. 3 Forms generated based on the revolution hyperboloid.
Source: the authors.

Fig. 4   Hyperbolic paraboloid with curved edges, straight edges, decomposition.
Source: the authors.

versatile forms for application in roofing projects due to the possibility of varying its compositions. It is a double curvature form defined by the combination of sets of two opposite and perpendicular parables. The curved-edged paraboloids known as horse saddles and the straight-edged hyperbolic paraboloids and their compositions. Each point of the curved surface of a hyperbolic paraboloid can be defined by two straight lines" [14].

3.3 Colònia Güell Church and Crypt

In 1898 Gaudí was invited by Eusébio Güel to design the church and Crypt of Santa Coloma de Cervelló, in Catalonia, and to define the project he carried out several experiments using funicular models over the ten years. The work began in 1908, however in 1914 only the Crypt had been built, due to various factors the Güel family decided not to complete the work. Among the factors that influenced the stoppage of the work are the delay of the work, the First World War and the death of the mentor of this and other works of Gaudí. Bak et al. [15] point out that several local techniques in masonry were applied in the Crypt; this factor influenced the delay of the work because it depended on artisans. However, even though the work was not completed, it was considered a World Heritage Site, as it is a mark of Gaudí's break from previous styles. This promoted an evolution of Gaudí's knowledge through the experimentation of form, materiality, and the synthesis of his technical and structural knowledge with nature as reference

[16].

Fig. 5 highlights the inner elements of the Crypt, such as thinner basalt central pillars due to the higher strength "450 N/mm^2", compared to the outermost lower strength masonry "250 N/ mm^2", therefore wider. The central pillars are slanted locked by a parabolic arch transition element, which receives the transverse ribs also with thinner burnt ceramic arches. This structure shows Gaudí's mastery when applying materials with different strengths, as well as the inclination of the pillars to receive the arches of the chapel, not built. The crypt roof slab would welcome visitors, so the floor ribs in conjunction with the prismatic folding edge walls help minimize the effects of the winds [15].

In front of the Crypt Gaudí created balconies where we can observe: asymmetrical catenary arches (Fig. 6-left). These arches are born from the pillars and die in transition ribs (Fig. 6-right) double-swiveling columns. These columns can be classified as a rotating hyperboloid as they have their sections rotated around the main axis of the column. In Fig. 6 (right), it is observed that the thin masonry shells differ from traditional models in that each of their irregular planes is a fragment taken from the decomposition of a distinct hyperbolic paraboloid, which together help to build a common geometric shape, but generated by means of straight elements in masonry [17].

In this small work the architect applied the different masonry, in known geometric forms, but with different

Fig. 5   Image of the central atrium of the Iglesia de la Colònia Güell crypt.
Source: the authors.

Fig. 6   (Left) external view referring to the main entrance of the crypt; (right) image showing the structural elements in catenary arches between the pillars and the main wall; and the vaults in hyperbolic paraboloids.
Source: the authors.

compositions, such as Catalan vaults, hyperbolic paraboloids [11].

3.4 Templo Expiatorio de la Sagrada Familia

The works of the Templo Expiatorio de La Sagrada Familia began in the late nineteenth century, but due to its complexity the temple is still under construction. Gaudí, in 1883, was invited to assume the project of "Francisco de Paula del Villar y Lozano in neo-Gothic style", however he proposed a much bolder project, and

devoted himself to this work until his death in 1926 [18]. Gaudí's masters and disciple builders struggled to complete the work due to the complex shapes and the destruction of designs and models in 1936 during the Spanish Civil War [19].

Fig. 9 proved that the rotating hyperboloids were applied to the Sagrada's work on the roofs to allow light to pass through, and as a surface element that rests on the arches and unites the ensemble.

Mark Burry took over the work of the Sagrada

Familia in the late 1980s; he began to get involved in the process already at the end of his architecture education in Australia. Burry, in an interview with Liza Fitzpatrick [20], states that Antoni Gaudí's genius was to design "a church in the Gothic tradition" ahead of his time. He notes that Gaudí elegantly applied the "great buttresses" of this architectural language.

Gaudí, in the last twelve years of his life, developed methods to enable his collaborators to finish the work; among other instruments, he made use of drawings and models for form exploration, especially plaster models to represent the openings and closures of the Sagrada Familia, roofing and facades [13].

Burry and Burry [13] point out that by combining a broad knowledge of geometry and observing the stresses and deformations that occurred in the wires, Gaudí created a grounded method of experimentation and produced unusual shapes by decomposing and mixing surfaces.

In the Sagrada Familia church it is observed that catenary funicular arches were applied to the entrance arch (Fig. 10), the high altar, the central nave and the sides, aiming at the dispersion of the internal loading of the building in favor of wider spaces. The hyperbolic domes present on the high altar (Figs. 8 and 9) represent the union of at least four capitals that are originated by a rotating hyperboloid of a leaf around the central axis, but asymmetrical, allowing light to enter. In the towers, and in the dome to the left of Fig. 10 were applied the overlap of twelve small slightly curved hyperbolic paraboloids, which were rotated around the central axis [10].

Bak et al. [15] point out that the application of the high, rotating columns in the Sagrada Familia made it seem like "the Gothic aerial arch systems applied to the Crypt were superfluous". Although we recognize parallels between the conception of the Crypt and the Sagrada Familia, the structural approach is differentiated. In the Sagrada Familia the arches unload on the raised pillars but keep the trajectory of the center of gravity stress of each structural element, as shown in Fig. 10. The authors note that the supporting structure of the Sagrada Familia was determined graphically, while the design of the Colónia Güell church used three-dimensional wire funicular models to determine the supporting structure of the church.

Fig. 7   (Left) external image referring to the front view of the Sagrada Familia Church; (right) inside image of the church's central atrium toward the top of the high altar.
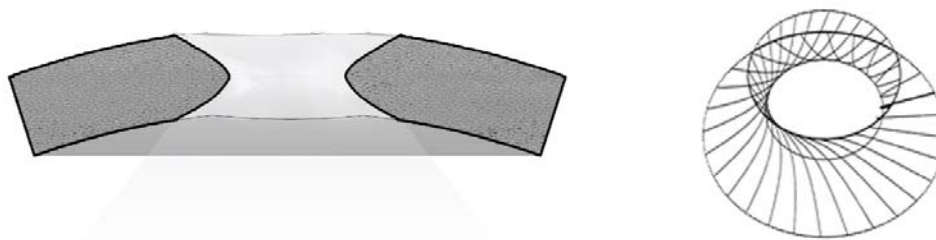Source: the authors.

Geometric Shape, Structure and Material in Antoni Gaudí's Work: The Colònia Güell Crypt and the Templo Expiatorio de la Sagrada Familia

615

Fig. 8 Internal image signaling the rotating hyperboloids in the connecting part of the existing pillars in the Templo Expiatorio de la Sagrada Familia.
Source: the authors.

Fig. 9 Rebound rotating hyperboloids applied to the Sagrada Familia.
Source: the authors.

Fig. 10 External view of the church.
Source: the authors.

Fig. 11 (left) shows the image of the internal view of La Sagrada Familia church, highlighting the high altar with its catenary arches and raised pillars. In Fig. 11 (right) shows as double pivoting column. The cross sections of these pillars consist of a polygon whose geometry alternates along the height as the number of edges increases. This polygon starts from an in-sided star. During the transition from one section to another Gaudí overlaps two helical rotations taking as its base axis the axis of the central element. Along the length he caused "rotations inversely proportional to the height, clockwise and the same rotation counterclockwise" [21]. Along the height the cross-section changes between the basic shapes, n-point star almost circular, square, parallelogram and rectangle. At the top starts the transition of elements that support the roof, as highlighted in Fig. 11 (right). According to Huerta [16], the pillars were designed to collect the loads of the upper elements of the roof and to transfer them to various fixed points in the ground.

Mark Burry points out in an interview that in the early 1990s computer aided design (CAD) programs lacked the facility to model the complexity of the Sagrada Familia, so he adapted aeronautical engineering software [20]. In the late 1990s parametric software was to be recognized in the context of architecture. Burry and Burry [13] highlight its application in models of the Sagrada Familia, "varying the parameters, geometric surfaces, individual components within the composition to improve the fit to the various conditions measured from the physical plaster models could be achieved within the software itself, which was then parametric, providing associative geometric information" [13].

3.5 The Modeling of the Templo Expiatorio de la Sagrada Familia

Parametric modeling was performed using Rhinoceros 6 with the visual programming tool Grasshopper version 6.1.18023.13161. In the analysis we sought to identify the similarities between Gaudí's experimental process known as funicular and the form-finding process.

As shown in Fig. 12, we started from a straight line fixed at two points, the relative distance of the gaps of the Sagrada Familia. This line was subdivided into equal spaces and uniform loads were applied along the line. At this moment, we observed the formation of a catenary curve, highlighted in red in Fig. 12, a traction funicular, referring to the acting stresses on the wire. Therefore, it is noteworthy that the digital parametric modeling allowed observing phenomena similar to physical experiments, as well as their inversion.

In order to create a simulation of the main structure we used an open grasshopper application called EMU, produced by Emil Poulsen, as a part of the "master's degree in structural engineering and building technology at Chalmers University of Technology". It was conceived for grid-shell curved structures in the form-finding analysis with six degrees of freedom, allowing the simulation of buckling, torsion and flexion in bi-axial simulations [22].

From the analysis of deformation versus form, we proceed to the structure modeling with the Kangaroo software. The second verification was aimed at understanding the phenomena of the stability of the structure; in this sense, we simulated the main bone structure, pillars and arches without the surface elements. The elements were simulated as solid beams of homogeneous section. In order to observe the deformations that occurred in Gaudí's experiments, we considered more slender elements than the architect applied in the Sagrada Familia. Fig. 13 shows the blue buckling of the columns. As highlighted by Huerta [16], Gaudí solved the buckling in the arches by increasing their dimensions at the points with the highest stresses; this last solution is found in the Colònia Güell Crypt and the Sagrada Familia entrance arch in Fig. 9.

To understand the deformations that occurred in Gaudí's experimentation some elements were suppressed in the modeling. Fig. 13 shows that the original

Geometric Shape, Structure and Material in Antoni Gaudí's Work: The Colònia Güell Crypt and the Templo Expiatorio de la Sagrada Familia

617

Fig. 11   (Left) the central atrium of the church; (right) pillar construction scheme.
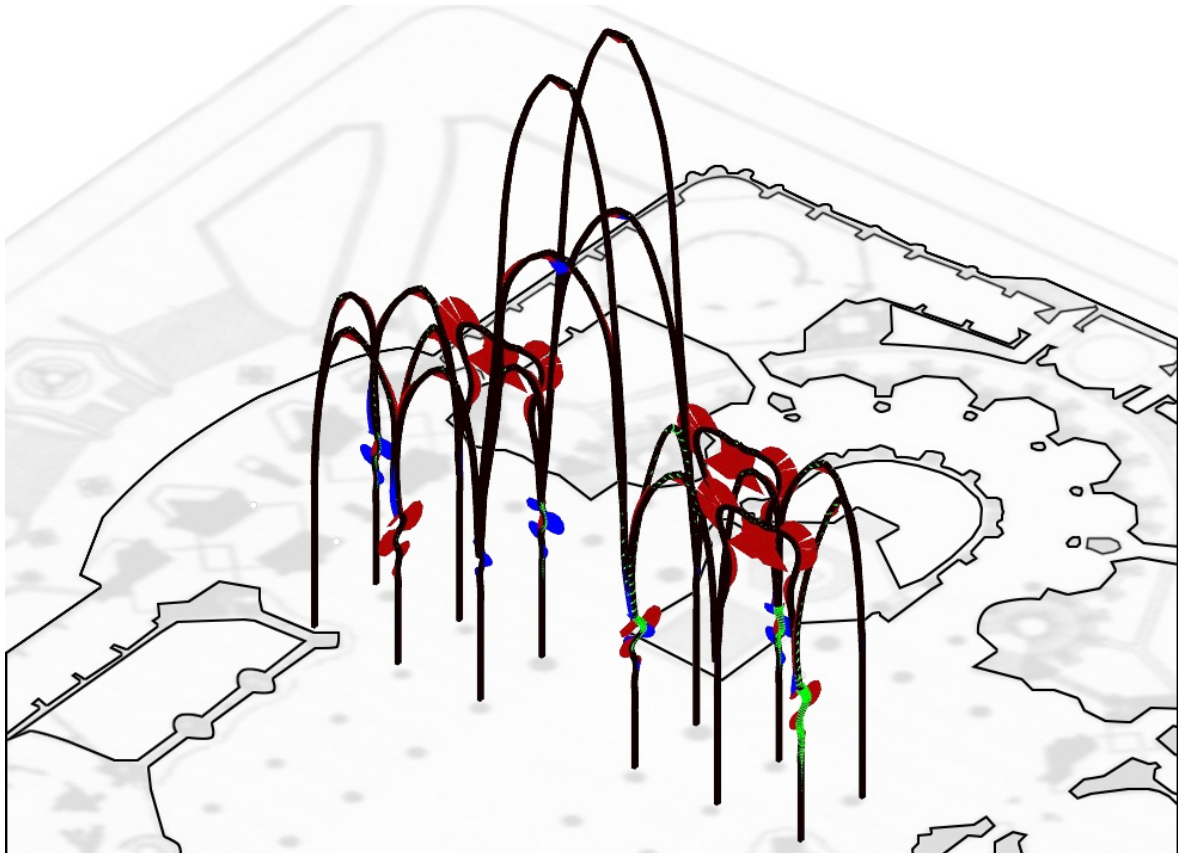Source: the authors adapted of Ref. [21].
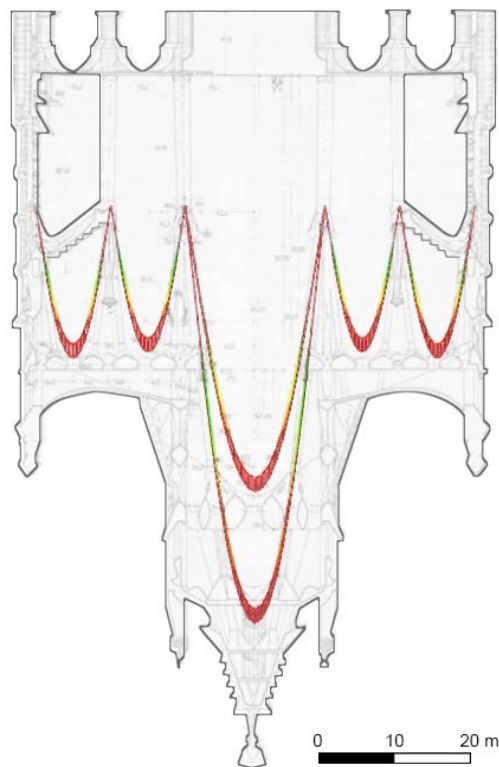
Fig. 12   Funicular modeling.
Source: authors' modeling based on the section presented in Ref. [15].
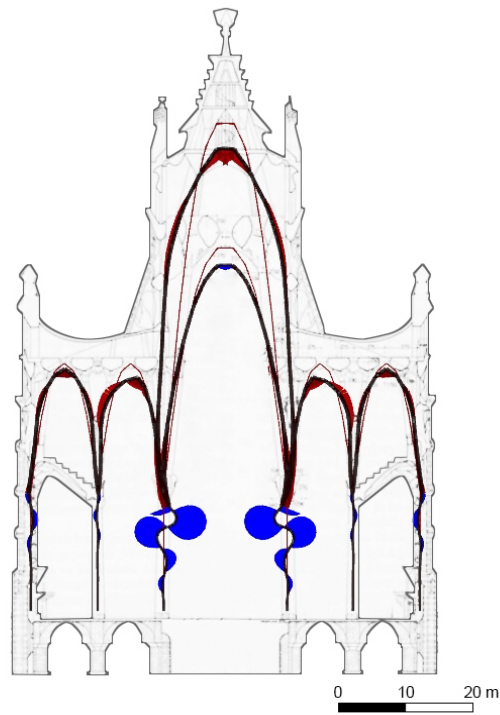
Fig. 13   Structure modeling of key elements.
Source: authors' modeling based on the section presented in Ref. [15].

Fig. 14   Structure modeling in space.
Source: authors' modeling based on the section presented in Ref. [15].

Geometric Shape, Structure and Material in Antoni Gaudí's Work: The Colònia
Güell Crypt and the Templo Expiatorio de la Sagrada Familia
619

catenary is modeled on a thin red line as well as thickening at the most demanded points.

The third modeling shows the isometric bone structure of the Sagrada Familia. Through modeling it is possible to realize the importance of the main structural elements in the stability of the set, the central nave and the side naves, as shown in Fig. 14.

The analysis highlights the importance of the locking elements of the set, in particular the perpendicular catenary arches, as well as the role of domes and vaults between the arches stabilizing the set in the direction perpendicular to the central nave. At the highest points of the catenary arches, flexion and torsion of the arches are seen in red. We note that Gaudí solved this problem because the upper slabs work as a lock of the set, as well as the slabs next to the foundation.

On the inside, Gaudí applied the straight pillars with the design of the pillars in trees, allowing them to bifurcate in different directions helping to stabilize the set. Huerta [16] also points towards Gaudí's perception of the concepts of global stability.

As highlighted above, the modeling was performed in a simplified way with thinner elements to observe the phenomena perceived in Gaudí's experiments, therefore we note that the analysis does not represent the complexity of the complete work of the Sagrada Familia, but brings with it the perception of approximation of the deformations felt in the architect's initial models. Poulsen [22] highlights the importance of physical experimentation to observe structural phenomena, as well as the potential of parametric modeling in the observation of deformations in what we call form-finding.

3.6 Summary

In summary, it can be highlighted by the analysis performed in this work with the evaluation of the two works, that Gaudí's design process was supported by physical experiments called funicular, in the domain of curved forms and surfaces, in structural knowledge applying concepts of transitions with loading transmitted by gravity lines.

Another relevant factor is that Gaudí's work can be considered as tectonic because it is supported by the search for local techniques in the use of Catalonia masonry, as well as applied to the search for efficient structures suitable for the material (funicular, form-finding) and as highlighted by Frampton [23] in search of the valuation of the constructive culture.

In a critical analysis through studies and modeling it is possible to highlight that, unlike architects such as Félix Candela and Eladio Dieste, who applied predominantly large curved surfaces designed for reinforced materials, Gaudí valued the concept of main bone structure, in funicular arches and pillars, complemented by small surface elements, hyperbolic domes, elliptical paraboloids, and vaults. At the Crypt these factors are most striking due to the different materials in the pillars, ribs and surfaces. In his works the structural function of the elements is highlighted, as an example, in the slanted pillars of the Crypt, etc.

The experiments carried out in the Crypt were decisive in defining the structure of the Sagrada Familia, with a mastery due to the small arches that are born in the pillars supporting the surfaces such as the vaults and domes that lock the set.

Therefore, Gaudí's experimental process defines his search for structural efficiency, in particular with the funicular arches and the contribution to future generations in the search for form efficiency, as well as in the definition of form-finding concepts, where there is a direct relationship between shape, loading and deformation in parametric modeling, indicating the search for morphological concepts as highlighted by Oxman [5].

4. Conclusions

In the area of architecture, it is relevant to rescue the construction techniques recognized as vernacular, such as the work of Antoni Gaudí in relation to Catalan traditions in the use of masonry, based on

geometric knowledge, in experimentation, associating the local material in search of structural efficiency combined with the functionality of the architectural project. Understanding geometric concepts associated with structural efficiency and materiality allows new architects to seek expressive but efficient forms.

One of the main structural strategies adopted by Gaudí to balance the loads and carry the loads by the center of gravity of the structural elements was the application of transition elements on pillars, arches, brackets, among others. The architect valued the main structure and used different materials in the bone structure and surfaces, applying the most resistant in the most demanded places, thus demonstrating a mastery of the strength of the materials.

The research looks at the parallel between Gaudí's funicular concept and form-finding in current parametric modeling, in the relation of curved shape modeling and its constructability, especially in loading, deformation and stress.

The identification of each structural and formal element applied by Gaudí has been widely discussed in other works, but until today its isolation and understanding are difficult for teachers and students to understand. In the analysis between the two works it is possible to perceive the application of similar elements, but in different scales and in an evolutionary way.

The research highlights that the recovery of structural concepts already used in the past, in an efficient way, can assign a new meaning in the delimitation of architectural space. This factor can be observed by several contemporary architects who are guided by constructive and compositional techniques, disseminated by icons of experimentation, such as Antoni Gaudí, however, with the use of various materials—such as steel, wood and concrete—that reinterpret the techniques addressed by the Catalan architect, but in different ways, related to the structural capacity and plasticity of each of the materials.

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